A MULTIDISCIPLINARY DESIGN OPTIMIZATION APPROACH TO SIZING STOPPED ROTOR CONFIGURATIONS UTILIZING REACTION DRIVE AND CIRCULATION CONTROL

Dr. Dimitri N. Mavris
Associate Director and Manager

Mr. Jimmy Tai
Graduate Research Assistant

Dr. Daniel P. Schrage
Professor and Director

Aerospace Systems Design Laboratory
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0150

Abstract

Over the years, the U. S. rotorcraft industry and NASA have conducted numerous studies to determine possible candidates for a potential High Speed Rotorcraft Concept (HSRC) and to identify and provide suggestions and solutions to technology issues that might hinder the development of such concept. Many feasible concepts have been proposed and studied including the tilt rotor, the tilt wing, the folding tilt rotor, the variable diameter tilt rotor, the advanced canard tilt rotor, the coaxial propfan/folding tilt rotor, and the stopped rotor/wing configuration. Among these concepts, the rotor/wing still remains the least studied compared with the other candidates. This can be attributed primarily to lack of suitable analytical tools to assist the design process and to unfamiliarity with this unconventional concept. The potential success of a stopped rotor/wing configuration can only be determined through direct performance comparisons with the concepts mentioned above using analytical methods of comparable sophistication. The intention of this paper is to address the issues associated with sizing and optimizing a stopped rotor/wing configuration which incorporates a tip jet drive system and Circulation Control devices. In addition, a methodology has been formulated and is presented which forms a foundation upon which a new sizing code capable of handling this unique concept can be developed. Since the subject of this paper deals with a concept that enables relatively uncommon technologies, a review of the physics associated with these concepts is also presented.

Symbols

A_j	Area of Circulation Control Slot Opening (ft^2)
C_μ	Blowing Momentum Coefficient (nd)
C_T	Thrust Coefficient (nd)
F_j	Tip Drive Force (lbf)
h/c	Slot Height to Chord Ratio (nd)
m_j	Circulation Control Mass Flow (lb/sec)
$\dot{m}_j$	Tip Jet Mass Flow Rate (lb/sec)
M_∞	Freestream Mach Number (nd)
P_d	Rotor Blade Duct Pressure (psf)
P_∞	Freestream Pressure (psf)
q_∞	Freestream Dynamic Pressure (psf)
R	Rotor Radius, or Trailing Edge Radius (ft)
S	Wing Area (ft^2)
T_{o_d}	Total Temperature in the Rotor Duct (^oF)
P_{o_d}	Total Pressure in the Rotor Duct (psf)
V_j	Circulation Control Jet Velocity (ft/sec)
	Tip Jet Nozzle Exit Velocity (ft/sec)
V_T	Rotor Tip Speed (ft/sec)
ΔP	Change in Pressure Over CC Jet (psf)
η	CC Jet Width (ft)
Ω	Rotor Rotating Frequency (rad/sec)
ρ	Density ($slugs/ft^3$)
σ	Solidity (nd)

I. Introduction

NASA and the U. S. helicopter industry have studied over the years a series of candidate rotorcraft configurations suitable for high speed cruise velocities in order to fulfill a possible inter-city transportation need which calls for vertical take-offs and landing capabilities in vertiport sites located downtown. Such High Speed Rotorcraft Concepts (HSRC) must be able to combine in a single reliable and affordable configuration the hover efficiency and low speed agility of the helicopter, while still maintaining low downwash characteristics, as well as the high speed cruise, maneuver capability, and handling qualities commonly associated with fixed wing aircraft. According to the mission requirements depicted in Figure 1 below, this HSRC must be able to vertically takeoff and land (VTOL), hover for 2 to 15 minutes, depending on the mission, transition to fixed-wing mode, and cruise at speeds up to 450 knots. Furthermore, it must be able to carry 6000 lbs of payload (military transport) or thirty passengers (civil transport), depending on the mission, for a distance of 600-700 nautical miles. Since no aircraft is readily available to satisfy all these requirements, contracts were awarded to all four major helicopter companies to investigate this problem.[1,2,3,4] The studies conducted by these companies produced a list of possible candidate aircraft and identified problem areas where technology is either not available or require further consideration for development. Each of these companies then picked two of the most promising concepts and pursued them.

In parallel with these industry studies, the researchers at the Systems Analysis Branch of NASA Ames compiled their own list of candidates and pursued their own analyses. This list of NASA possible concepts included an advanced tilt rotor with canards, a tilt-wing, a folding tilt rotor, a coaxial propfan/folding tilt rotor, a variable diameter tilt rotor, and a stopped rotor/wing concept called the M-85[5] (represented by Figure 2). Due to lack of funding, the HSRC program was officially canceled in 1992, and most of the companies continued to study their concepts on their own. Georgia Tech, due to its commitment to its rotorcraft graduate design program, also continued to study these various concepts. Among these various candidates, the stopped rotor/wing configuration remains the least studied due to lack of analytical tools to assist the design process and due to the unfamiliarity with the physics behind this concept.

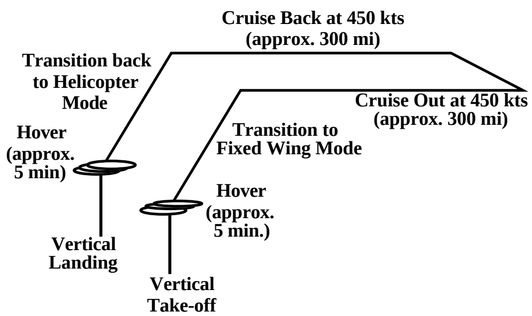

Figure 1: Mission Profile of the HSRC

Based on these mission requirements, it is obvious that a viable high speed concept must primarily be efficient in cruise and secondly, in hover. Since the aircraft spends most of its mission flying in a fixed wing configuration, it is unnecessary to penalize the aircraft with a heavy transmission and gearboxes (which account for about 8-14% of the total helicopter weight) for its entire mission. Given the fact that the mission requirements call for only a few minutes in the hover mode, the designer should accept higher specific fuel consumption and lower efficiency during takeoff, hover, and landing and take advantage of the benefits that such a concept has to offer at high cruising speeds. Furthermore, the high speed requirement will most likely be the predominant sizing design constraint (according to initial preliminary performance estimates); therefore, the engines should have enough excess power to accommodate the hover power requirement. Based on this rationale, the high speed stopped rotor/wing concept appears to be suitable for this mission and should be considered as a legitimate candidate.

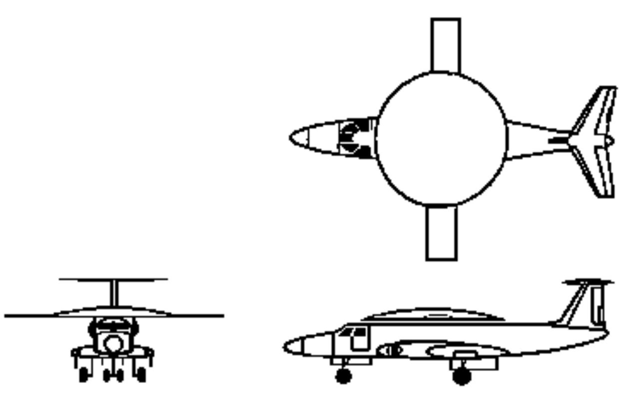

Figure 2: Stopped Rotor/Wing Concept (M-85)

Therefore, the objective of this investigation and henceforth this paper is to provide the designer with a methodology to properly analyze the stopped rotor/wing concept. Since this concept is rather unique, a general discussion of what is a stopped rotor/wing is offered to familiarize the reader with this concept. Also, the fundamentals of reaction drive propulsion system and Circulation Control airfoils and rotors will also be presented.

II. The Stopped Rotor/Wing Concept

A stopped rotor/wing aircraft is a unique concept because it combines together in one configuration the hover capability associated with rotorcraft and the high speed capability and cruise efficiency of an airplane. The Georgia Tech configuration is a derivative of NASA Ames' M-85. It is a convertible airplane, labeled as the GTM-85, powered by an all pneumatic drive system and makes use of a dual purpose rotor/wing lift system. These two attributes together provide a simple and light weight design.

A three view schematic of the GTM-85 stopped rotor/wing concept is presented in Figure 2. This convertiplane is designed to takeoff, hover, and proceed through the low speed flight regime as a tip jet rotor powered helicopter. Then, it accelerates in an autogyro mode to the conversion speed (i.e. speed where the rotor disc can provide sufficient lift without the use of the blades) where it most likely auto-rotates through its conversion phase. During conversion, a procedure similar to the one proposed for the Composite Research Aircraft (CRA)[6] can most likely be used to slow down and eventually stop the rotor. Finally, the aircraft rotor remains stopped during fixed-wing flight, and the two blades are located either in the unswept or oblique position for the cruise and high speed flight. For the re-conversion maneuver, the rotor starts its rotating motion by using aerodynamic forces and by reactivating its tip jets.

The GTM-85's rotor system consists of a lifting center body disc (hub fairing), and two lifting surfaces that act both as rotor blades and wings, depending on the mode of operation. Both the circular hub fairing and the blades are envisioned at this point to be rotating at the same rotational speed. The purpose of the center-body disc is two fold. It provides the necessary lift to assist the aircraft during conversion and forward flight, and secondly, it serves as an aerodynamic fairing for the structure and equipment in the hub area, thus providing the aerodynamic cleanliness required for efficient high speed flight. This arrangement should provide sufficient support for the short and stiff blades. The actual dimensions of the hub fairing disc is determined based on its lift and drag capabilities and on the desired conversion speed range. The size of this disc needs to be kept to a minimum in order to reduce drag in forward flight and to avoid lift potential and hover efficiency (Figure of Merit) degradation in the helicopter mode.

The two rotor blades are non-retractable and extend from the large circular hub fairing which is estimated to be in the order of 50 to 60% of the rotor diameter (depending on performance requirements). The blade airfoil sections are

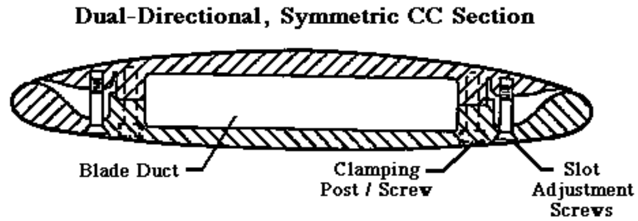

Figure 3: CC Rotor Blade Airfoil Section

elliptical in shape, similar to the ones presented in Figure 3.[7] The use of elliptical or symmetrical airfoils eliminates the problems created when one of the rotor blades (after conversion) finds itself operating with its trailing edge facing the freestream (acting as a wing leading edge), thus degrading the aircraft's performance. In hover and low forward velocities, the required lift is provided by the blades only; therefore, in order to make these airfoils more aerodynamically efficient, Circulation Control devices are integrated into them with either single or dual Circulation Control slots (refer to Figures 3 and 4).[7]

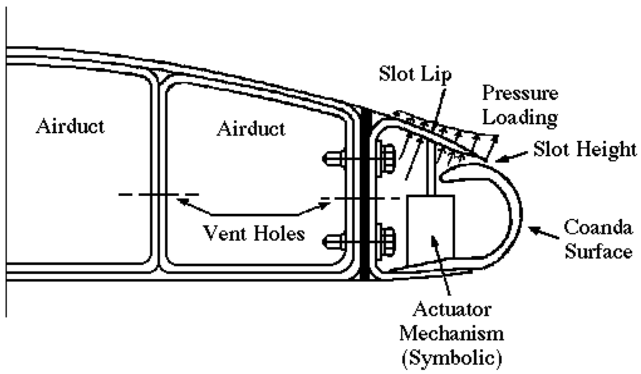

Figure 4: Blade Section Profile for the Tip Jet/CC Airfoil

Depending on the value of the blowing coefficient, C_μ, tests at the Carderock Division Naval Surface Warfare Center (CDRKNSWC), formerly known as David Taylor Naval Research Center (DTNRC), have indicated that these airfoils provide superior C_L values compared to that of equivalent NACA series airfoils without varying the pitch angle of attack and that they are practically unstallable. These rotor blades are fixed geometrically in pitch, and a pneumatic device is used for rotor control (blowing collective and cyclic). The rotor (hub fairing and blades combined) are driven by reaction jets which are exhausted to the atmosphere by either adjustable or dual directional tip nozzles with no tip burning (refer to Figure 5).[7]

III. Pressure Jet (Reaction Drive) Discussion

A pressure jet or tip jet driven rotorcraft configuration is defined as one in which the propulsion is provided by heated air or gas exhausted through a jet nozzle at the helicopter rotor blade tips.

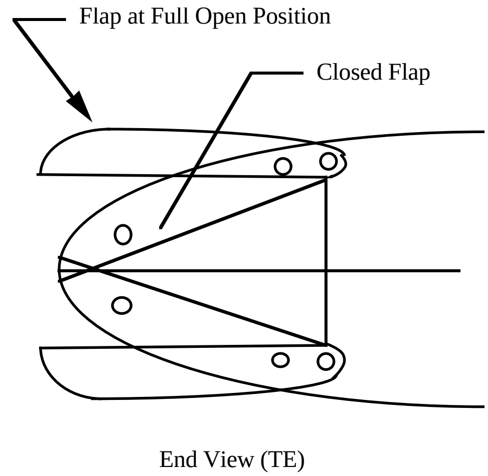

Figure 5: Tip Jet Nozzle Arrangement

The stopped rotor/wing concept discussed here is powered by such a system which transmits the required power pneumatically using lightweight ducting and a diverter valve. This diverter valve directs either high-pressure warm gas (roughly 900 ^oF) from the engine exhaust ("warm" cycle), or high pressure air from the compressor ("cold" cycle), or hot, pressurized gas ("hot" cycle) to the rotor blade tips to drive the rotor. The terms "hot" cycle, "warm" cycle, and "cold" cycle refer to the temperature of the propulsive gas as it leaves the gas generator and are obviously relative.

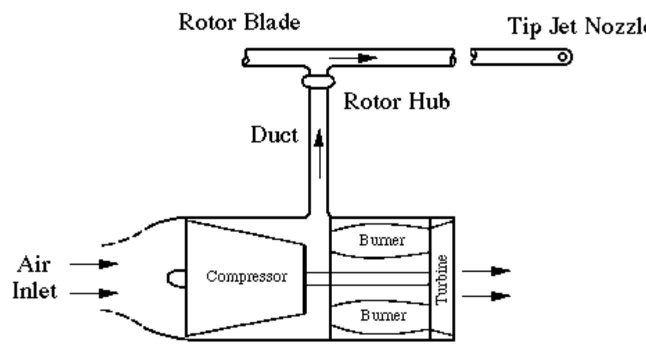

Figure 6: "Cold" Cycle Pressure Jet

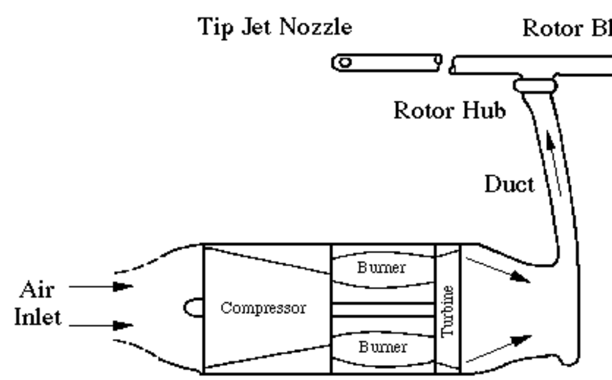

Figure 7: "Hot" Cycle Pressure Jet

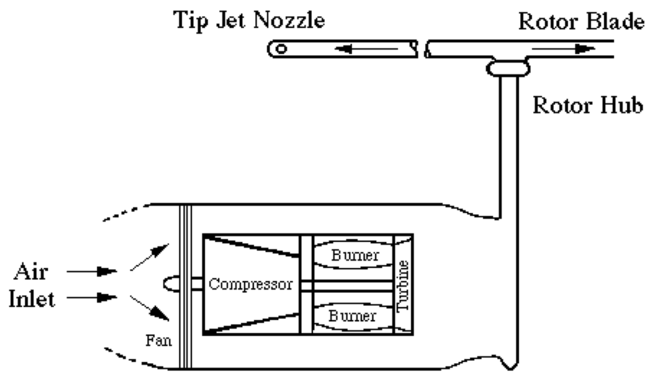

Figure 8: "Warm" Cycle Pressure Jet

In general, cycles which employ propulsive air directly from a compressor are termed "cold" cycles (Figure 6), while cycles which employ propulsive gas from the turbine exhaust are called "hot" cycles (Figure 7). Finally, cycles that use a mixture of cold air (turbofan bypassed airstream) mixed with the engine exhaust are termed "warm" cycles (Figure 8). The selection process of the most suitable pressure jet cycle for the rotor/wing can be viewed as an exercise in compromise where the thermodynamic advantages of a more efficient cycle are weighted against the aerodynamic reduction in efficiency and the structural problems caused by the higher temperature. In order to assist the designer in selecting a pressure jet cycle, the relative efficiency of each cycle needs to be examined.

Overall cycle efficiency is an important parameter in the designer's decision making process. Since the propulsive efficiency of the pressure jet is not very high at normal rotor tip speeds, one has to compensate for this inefficiency by generating the propulsive air or gas with the maximum possible efficiency and make use of the lightest weight machinery available.

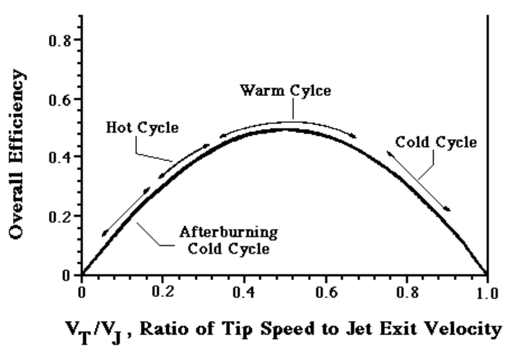

Figure 9: Pressure Jet Cycles' Overall Efficiency

Figure 9 shows the overall efficiency variation with the ratio of rotor tip speed to jet exit velocity.[8] This has been generated by plotting out data gathered experimentally or analytically for the various concepts. According to Reference 7 the "hot" cycle appears to be the best candidate from a thermodynamic point of view because it provides the most energy, but its overall efficiency does not fair as well as that of the "warm" cycle (Figure 9). Furthermore, the rotor blade dimensions, which are limited by the duct size, will have to be enlarged to increase the available power so that sufficient power is provided for the "hot" cycle configuration. On the other hand, the "cold" cycles (by increasing pressure or by tip burning) can develop more power than the "hot" cycle independently of the blade duct size, but they are not as efficient as the "warm" cycle (see Figure 9). Therefore, inspection of Figure 9 indicates that the "warm" cycle appears to be the most efficient cycle.

Regardless of which cycle type is selected, the use of the pressure jet eliminates the weight and complexity of shafts, gearboxes, clutches, and propellers that are used in a turboshaft driven aircraft. Furthermore, an anti-torque tail rotor is not needed since there is no rotor shaft drive torque reaction on the fuselage. However, directional control during helicopter flight can be provided by a small yaw jet or fan located in the fuselage boom.

IV. Description of CC Airfoils and Rotors

Since the flow over the upper surface of a conventional airfoil cannot turn around the sharp trailing edge (velocity would have become infinite), the flow simply separates and leaves at the trailing edge. Similarly, the flow over a pure elliptical airfoil also separates but on the upper surface which gives poor performance characteristics. However, with the help of blowing or Circulation Control, flow remains attached around the trailing edge and separates at some point on the lower surface; therefore, improving the airfoil performance.

A typical CC airfoil is characterized by a relatively thick section (15-50% thick), by an uncambered or small amount of camber, and by a tangential blowing slot on the upper surface near a rounded aft end (Refer to Figure 3). In order to attain airfoil (or rotor) Circulation Control, pressurized air usually bled from the engine is first ducted to the rotor hub through a diverter valve and then pumped to the rotor blades through a modulating system (a cyclic control valve). Once inside the blade, the air is ejected out a continuous slot located along the blade trailing edge. The slot through which the air is ejected is positioned near the trailing edge such that the slot flow is tangent to the airfoil surface. The slot flow is exhausted at a speed greater than the local external flow; therefore, energy is added to the boundary layer across the mixing boundary, and this action permits the upper flow to remain attached. The ejected air obeys the so called Coanda principle as it remains attached and curved around the bluff-rounded trailing edge of the airfoil section. This phenomenon is attributed to a balance between the centrifugal force applied to the flow around the rounded trailing edge and the pressure differential produced by the jet velocity (see Figure 10).[9]

The slot at the trailing edge is similar to that of the throat of a converging nozzle, and it is usually formed by the internal geometry of the Coanda surface and the underside of the rotor blade (refer to Figure 10), but obtaining the most suitable slot height is by no means a trivial task. The slot height can either be fixed or adjustable by a set of pitch screws or some other mechanism. In general, as the slot height increases, gradual degradation of the airfoil's performance occurs for a constant value of C_μ. This behavior is caused by the dependence of the slot height to the jet kinetic energy. On the other hand, a decrease in slot height implies an increase of the CC jet velocity magnitude which could result in choking at the throat station which causes the flow to expand supersonically. This in turn can lead to jet detachment and can also cause loss of performance.

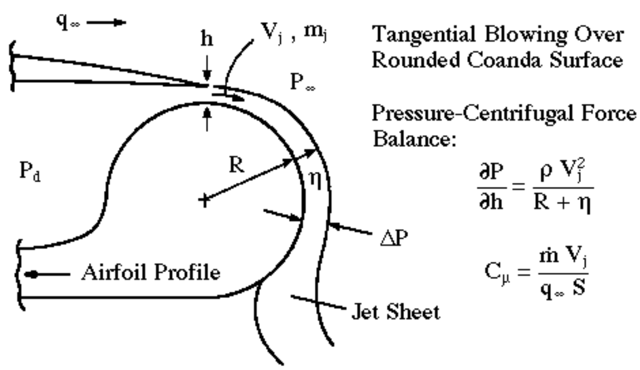

Figure 10: Coanda Effect

Blowing Momentum Coefficient, C_μ

Unlike conventional airfoils, the CC airfoil performance capabilities such as lift and drag are not only dependent on the section angle of attack but also on the level of blowing employed at the trailing edge slot. This blowing level is defined by the momentum coefficient, C_μ, which can be computed by:

$$C_\mu = \frac{m_j V_j}{q S} = \frac{\rho_j A_j V_j^2}{q S}$$

In order to obtain a solution for the momentum coefficient, the Circulation Control blowing jet velocity, V_j, and the associated mass flow rate, m_j, must first be determined. Workable expressions for V_j and m_j can be obtained by assuming that the gas inside the rotor blade undergoes an isentropic expansion from the rotor blade internal pressure, p_d, to the freestream pressure outside the trailing edge slot.[10]

Properties of a Circulation Control Rotor

Circulation Control airfoils have experimentally demonstrated high lift capabilities that are practically independent of the effects of varying dynamic pressure or angle of attack. In addition, the usage of a dual slot (bi-directional blowing using leading and trailing edge slots) can make the airfoil performance also independent of flow direction. These capabilities make a lifting stoppable rotor aerodynamically feasible. Some of the main characteristics and properties that best describe this CC concept have been compiled below. This summary is based on a thorough review of numerous related publications.[10]

1) A Circulation Control airfoil is for all practical purposes unstallable.
2) The lift generation capability of a CC airfoil is proportional to duct pressure, and it is practically independent of angle of attack.
3) The lifting effectiveness of a CC airfoil is independent of the type and thickness of the airfoil.
4) CC airfoils have demonstrated efficiencies comparable to conventional sections but at much higher lift coefficients and over a broader range of C_ls.
5) Blowing tends to increase the slope of the lift curve.
6) Blowing reduces profile drag and delays the encounter of compressibility effects. Critical and drag divergence Mach numbers associated with CC airfoils are substantially higher than conventional ones.
7) For helicopter applications, the CC airfoils have demonstrated the ability to maintain high transonic equivalent lift to drag ratios.
8) For lift coefficients less than three and for constant duct pressure, the lift is independent of the free stream velocity.
9) Large increase in CC airfoil rigidity is possible due to high section thickness.
10) Circulation Control offers a section lift capability approaching the theoretical inviscid maximum given by $C_{l\ max} = 2\pi(1 + t/c)$. This is possible due to the absence of leading edge stall.

These properties have been found to have the following effects when applied to rotorcraft rotors:

1) The substitution of CC for conventional blade pitch control simplifies the mechanical configuration of the rotor hub.
2) Higher harmonic control of the CC device is proven to reduce vibrations
3) CC action alleviates stall of the retreating blade of a helicopter rotor at high forward speeds.
4) Compressibility effects are alleviated on the advancing blade at high speeds.
5) CC airfoils using the proper blowing level can force the advancing blade to carry its share of the total lift and distribute it over a larger area of the rotor disc.
6) For the CC rotor, a cyclic jet deflection can be used in order to ensure that at every forward speed of the rotor there will be a constant aerodynamic moment at the root of the blade. In principle, blade flapping can then be eliminated.
7) A CC rotor can generate far greater forces than a conventional rotor of the same radius and solidity.
8) For installed flight conditions, a CC rotor requires more power than a conventional rotor of basically similar design.

V. Analytical Tools Selected

Engine Cycle Analysis

Regardless of which cycle type the designer selects, an engine cycle analysis method is needed to generate the necessary on and off-design point engine performance behavior. The quick version of NASA's Engine Performance Program (NEPP)[11] known as QNEP[12] was selected as a suitable tool for this task. NEPP and its simplified derivative, QNEP, are engine simulation computer codes which perform one dimensional steady state thermodynamic analyses of engine cycles. NEPP was originally developed by a joint effort between the Navy Air Development Center and NASA Lewis Research Center. QNEP is a much smaller version of its parent, but it basically performs the same task, modeling engine cycles with less number of features. In order to facilitate the modeling of the desired engine cycle, NASA Lewis has also developed a graphical user interface around NEPP called NPAS (NASA Propulsion Analysis Program).[13] This graphical interface is wrapped around NEPP, and it provides a method of representing and editing an engine cycle pictorially. By allowing the designer to graphically "build" the desired engine schematic, NPAS enables a better understanding of the engine cycle. Without NPAS, one would have to "construct" the engine model from a long list of namelists and from a large number of data arrays, a task which is both tedious and time consuming. One of the enhancements considered for future incorporation to NPAS is the option to generate QNEP input files directly off NPAS. This future capability has been assumed as a fact in the development of the methodology presented in this paper.

Component Map Generator

Generally, QNEP requires maps for the fan/compressor and the turbine(s). These compressor and turbine performance maps are similar in their use and scaling. These component performance maps are generated using MAPS, a program developed by Mr. Mark Waters (Eloret at NASA Ames). The engine design parameters required to build the component performance maps using MAPS include the number of fan/compressors needed, the fan pressure ratio, the overall pressure ratio, the adiabatic fan/compressor efficiency at 100 percent corrected rotor speed, the corrected rotor speed, the desired bypass ratio, the turbine inlet temperature, and the number of stages for each turbine.

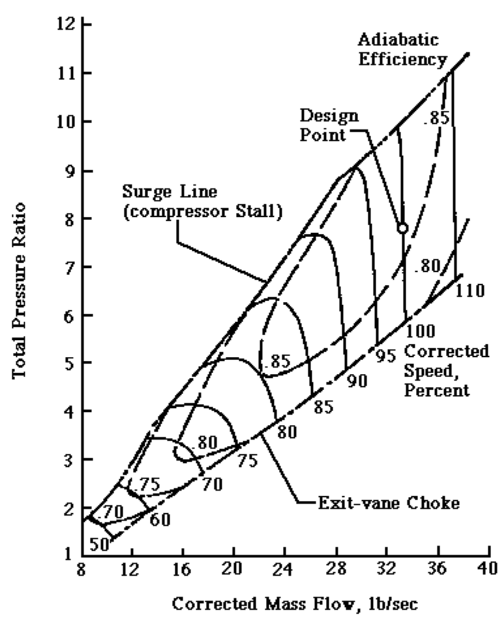

Figure 11: Typical Compressor Performance Map

A typical compressor performance map is depicted in Figure 11.[11] This map depicts a family of pressure ratios, corrected mass flow, and adiabatic efficiencies for a given stator angle and specified speed. In order to transform the map into a tabular form, QNEP uses a superposition of arbitrary lines called R lines on the map. An example of an R line representation is presented in Figure 12.[11] The user constructs these R lines by following the general shape of the surge line, which is defined as the locus of unstable operations of the compressor.[14] These R lines must not intersect each other, and they are assigned increasing values from the surge line.

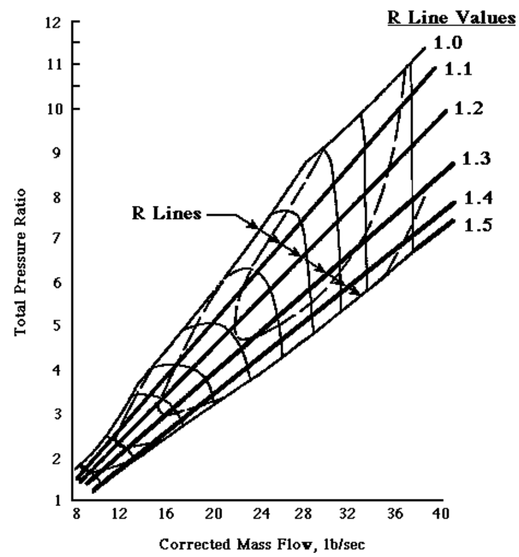

Figure 12: Typical Compressor Map Depicting R Lines

The resulting tabular form of the maps shows the pressure ratio, corrected mass flow, and the efficiency as a function of corrected speed, R value, and stator angle. The program, however, requires the user to input the design point of the map by specifying the R value, the corrected rotational speed, and the stator angle. Also at the design point, the designer can input the desired compressor pressure ratio and efficiency. With this information, the program defines a unique set of compressor map values. QNEP, at the design point calculations, uses the designer's performance input (desired pressure ratio and efficiency) and the component map design point information to compute the map scale factors, which will be explained and used further in the methodology.

As for the turbine performance maps, the user specifies the map design point by supplying the map pressure ratio and the corresponding corrected rotational speed. At the design point calculation, the designer provides the desired turbine efficiency, and QNEP determines the pressure ratio required to balance the work requirement on that shaft. With the pressure ratio, the turbine mass flow, and the map design point specified by the designer, the program computes the turbine map scale factors which will be used similar to those of the compressor scale factors.

Engine Weight and Dimensions

MARKII is an engine weight and dimension prediction code (developed by Mark Waters, NASA Ames), and it is based on historical, statistical data for the development of its weight equations. MARKII also estimates the nacelle weight using a Boeing's estimating technique. The program uses the input as well as the output information from QNEP's design point calculations. Parameters needed for the code include the fan pressure ratio, the fan and compressor efficiencies, the bypass ratio, the overall pressure ratio, the turbine inlet temperature, and the number of turbine stages.

Reaction Drive/CC Aerodynamic Analysis

The aerodynamic and thermodynamic analysis for a reaction drive rotor, using CC devices to improve its aerodynamics, can be performed through the use of CRUISE4 and CRUISE5. Both of these codes were developed by DTNRC, and they are based on a blade element strip theory approach and are the only codes available in the public domain capable of handling the effects of Circulation Control. CRUISE4 is used for the helicopter mode of operation, while CRUISE5 is used for the fixed-wing mode.

CRUISE4 has two basic calculation modes; one involves the estimation of the performance capabilities of a CC rotor for a specified set of control settings, while the other determines the control settings for a set of pre-specified trim conditions. For the first option, the user may request a performance analysis with or without trim. If the no-trim case is selected, then the user has to provide the code with values for the collective angle (θ), the cyclic and maximum pressure ratio at the hub, and both the cyclic and collective slot height to chord ratios (h/c). On the other hand, if the user selects the fully trimmed condition, a set of pitch and roll cyclic pressures and a set of slot height to chord ratios must be provided along with values for the cyclic and maximum rotor blade duct pressure ratios. In the second mode of operation, the user can specify the type of trim that he/she desires. The options are thrust trim only (no moment trim where the collective angle setting, the collective slot to height ratio, and the pressure ratio are specified), thrust and pitch trim, thrust and roll trim, and thrust, pitch, and roll trim. In all of these cases the problem can be formulated for either hub plenum flow modulation or active slot height control. The active slot height control option is an alternative to fixed slot heights or flexible slots that respond passively to a supplied pressure differential. In this active slot mode, blade root pressure is constant azimuthally, and blowing is modulated by collective and cyclic slot height control. The active slot height control calculations begins with a specified baseline slot height distribution along the blade span, and then all span station slots are controlled by a collective gain factor and a single set of cyclic level Fourier coefficients.

CRUISE4 also includes subroutines to calculate the structurally elastic slot deflection due to internal and external pressure, and it is able to determine the non-uniform inflow field as well as the spanwise variation of internal duct pressure due to centrifugal and frictional effects. Furthermore, it uses a blade element model to compute the rotor blade aerodynamic and dynamic behavior. Inflow options to this blade element model include the "classic" momentum inflow models and the more advanced vortex wake model. The momentum models are significantly simpler and quicker to use and are applicable up to rotor advance ratio values of 0.4-0.5. CRUISE4 also offers a choice of three momentum inflow models, the uniform inflow model which assumes a constant inflow velocity distribution over the entire rotor disk, the Glauert model which allows for a longitudinal inflow variation, and finally the White/Blake model which accounts for non-uniform inflow velocity.

Once the inflow velocity distribution is calculated using one of the models above, the TJ/CC rotor can now be trimmed. CRUISE4 first calculates the rotor blade pressure, temperature, and Mach number variations in both the radial and azimuthal positions. Next, the inflow velocity is computed, and the blade thrust, moment, and torque calculations are analyzed harmonically before the new flapping harmonics are computed. Subsequently, a trim matrix is built by repeating the inflow calculations using the baseline control settings from the trim trial but with thrust, roll, and pitch controlling parameters individually perturbed. This way the trim matrix sensitivity derivatives are obtained. At this point, the code solves simultaneously this set of linear equations whose coefficients have just been calculated in the previous step for the desired trim condition. The desired trim condition is determined in CRUISE4 by setting target values for the rotor thrust coefficient, C_T, and the pitch and roll moment coefficients. Once the code reaches a trim solution, it continues with a set of rigorous rotor performance calculations which predict the required rotor horsepower breakdown, the isolated rotor figure of Merit, the CC mass flow rate, and etc. For a tip et configuration, the performance results also include the tip-jet exhaust velocity, force, mass flow rate, the nozzle area.

Sizing and Performance Analysis

The actual mission analysis and vehicle sizing is performed by VASCOMP[15]. VASCOMP stands for V/STOL Aircraft Sizing and Performance Computer Program, a code developed by Boeing Vertol for NASA Ames which now maintains and enhances the public domain version of this code.

VI. Stopped Rotor/Wing Configuration Sizing Methodology

The rotor/engine sizing procedure for stopped rotor/wing configurations using reaction drive and Circulation Control devices is vastly different from that of conventional rotorcraft. The primary difference involves the unique coupling that exists between the rotor and the propulsion system. The required horsepower (HPreq) for conventional, shaft-driven rotorcraft is calculated once the aerodynamic properties of the rotor and the aircraft parasite drag are known. For torque-driven aircraft, the engine required power (available power) is readily computed by dividing the required power by the mechanical transmission efficiency. Thus, it can be stated that the sizing of the rotor is independent of the design variables used to engine sizing. The reaction driven, stopped rotor/wing concept with or without Circulation Control devices, however, requires a totally different approach since the rotor and the engine sizing are very closely coupled.

For this case, the torque (Q) needed to drive the rotor is not produced by a shaft at the center of rotation but rather by a force (F_j) created by the air ejected through the rotor tip nozzles ($Q = F_j \times R$). This tip drive force is dependent on the mass flow rate ($\dot{m}_j$) ejected and the net velocity at the rotor tip and can be computed by:

$$F_j = \dot{m}_j \times \left(V_j - V_T \right)$$

The tip jet velocity (V_j) is the key variable that couples the rotor and the engine, and it can be computed based on the assumption that the flow undergoes an isentropic expansion from the rotor blade internal pressure, p_d, to the freestream pressure outside the exhaust nozzle shown by the V_j expression presented.

$$V_j = \sqrt{2 \; R \; T_{od} \left(\frac{\gamma}{\gamma - 1} \right) \left[1 - \left(\frac{p_\infty}{p_{od}} \right)^{\frac{\gamma - 1}{\gamma}} \right]}$$

This equation shows that the jet exit velocity is dependent on the temperature and pressure inside the rotor duct. However, these two properties are the result of the engine exhaust conditions. Therefore, it is obvious that the rotor torque is heavily coupled to the engine flow properties and can only be determined through the engine cycle analysis.

Through a collaborative effort with NASA Ames' System Analysis Branch, the authors developed a design methodology to size such stoppable rotor/wing configurations which make use of reaction drives and Circulation Control devices. This overall design process is outlined in Figure 13 in the form of an algorithm and is presented next.

Setting Up the Problem

Step 1: The desired engine cycle type (cold, warm, or hot) which will power the candidate reaction driven aircraft is selected.

Step 2: A set of key engine and rotor design variables is identified for use in the engine/rotor/vehicle sizing optimization procedure. The engine selected parameters include the overall pressure ratio (defined as the fan pressure ratio times the compressor pressure ratio), the turbine inlet temperature, and the fan pressure ratio. The fan pressure ratio is a critical design variable in this study because it has the most significant influence on torque. While the rotor related design variables include the number of blades, rotor radius, collective angle, tip speed, ratio of lifting disc radius to rotor radius, and the blade utilization factor, which is defined as the ratio of duct area to blade cross sectional area. In addition, a range of thrust coefficients, C_T/σ 's, is identified for the vehicle sizing part of the analysis along with sizing conditions (i.e. velocity, altitude, temperature, a mission profile, and all associated mission requirements).

Step 3: The chosen engine cycle is modeled (i.e. engine schematic, flow and work load control laws, etc.) in NPAS using specific values for each of the engine parameters selected, and the engine characteristics and performance are output in a format compatible for use by QNEP.

Step 4: Given the engine design variables selected, MAPS is used to generate the fan, compressor, and turbine performance maps that will be used during the off-point design (i.e. mission analysis) stages of the sizing process.

Step 5: Furthermore, using the chosen cycle and design variable ranges as input to MARKII, the engine weight and dimensions are obtained as a function of mass flow rate.

Rotor/Engine Sizing

Step 6: Using the information from Step 3, QNEP is called to size the engine at the given sizing point flight conditions. This way, the referred thrust, fuel flow, and the pressure, temperature, and velocity conditions at the engine exhaust are determined.

Step 7: This information is then used to compute the pressure, temperature, and velocity losses that occur in the ducts linking the engine exhaust nozzle to the rotor hub. These losses are relatively simple to calculate using thermodynamic relations which account for the number of turns the flow goes through, the duct length, the Reynold's number in the duct, the smoothness inside the duct (friction coefficient), and the amount of insulation available (heat transfer through the duct walls).

Step 8: Once the thermodynamic properties of the cycle are obtained from Step 6, CRUISE4 (helicopter mode) and CRUISE5 (airplane mode) are called to carry out a comprehensive aerodynamic / thermodynamic analysis of the rotor for the desired range and increments of C_T/σ's. The outcome of this analysis determines the required mass flow to drive the rotor as a function of C_T/σ (and implicitly the gross weight of the vehicle). If the rotor sizing scheme can not reach convergence, then the engine design variables are perturbed (for instance, the fan pressure ratio, FPR) and Steps 3 - 9 are repeated in an iterative way.

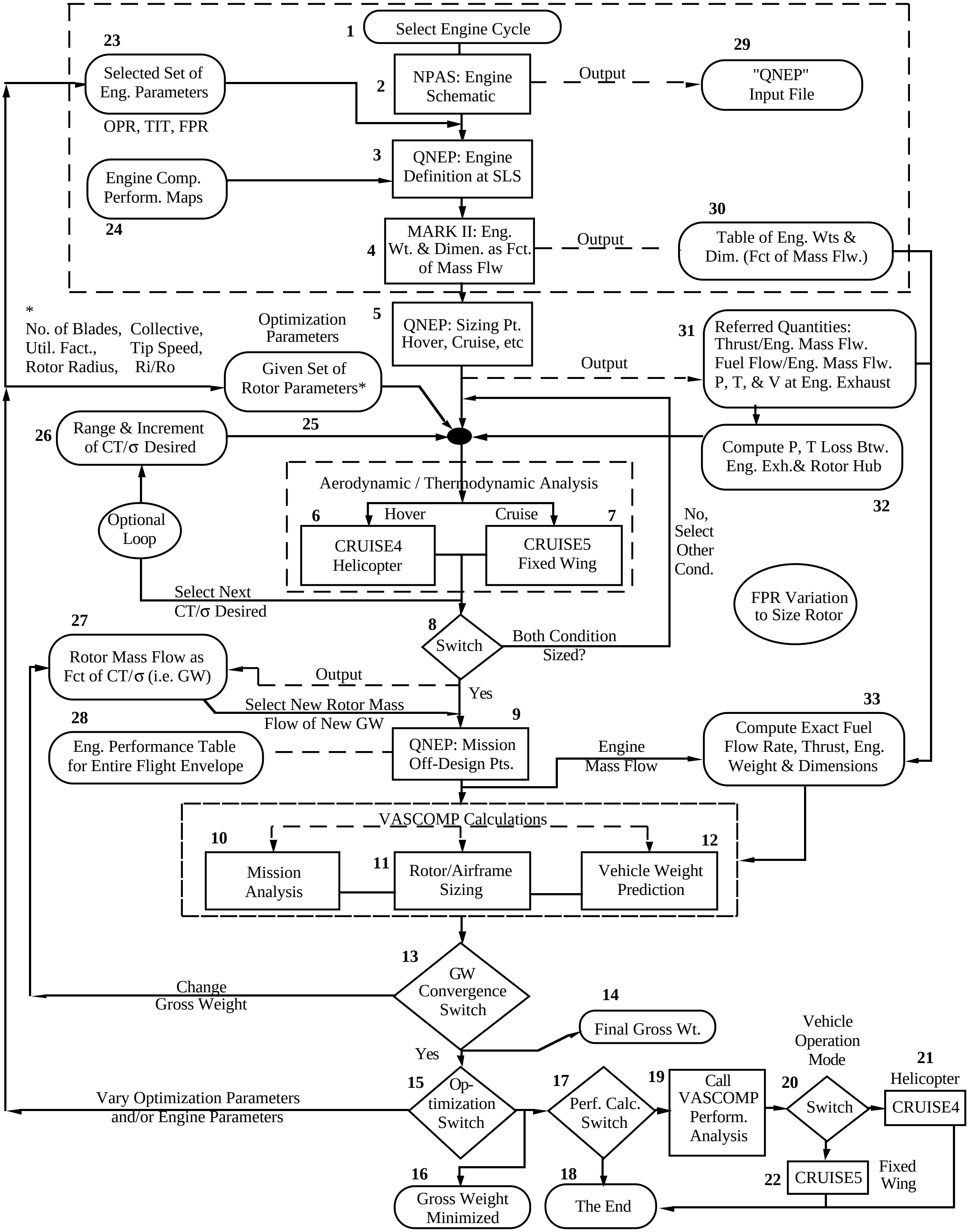

Figure 13: Overall Design Methodology for Stopped Rotor/Wing Configuration Utilizing Tip Jet and Circulation Control

Step 9: The information from the aerodynamic / thermodynamic analysis are used next to compute the exact fuel flow rate, thrust, engine weight and dimensions for a given C_T/σ. This task is accomplished by accessing the information that was generated by QNEP in Step 6 and through a table look-up of the results obtained by MARKII in Step 5.

Step 10: QNEP is called once again to generate a series of off-design point engine performance maps (i.e. referred horsepower/thrust, fuel flow rate as a function of altitude, Mach number, etc.) for the entire flight envelope. These tables willbe used by VASCOMP during the vehicle sizing phase (where the detailed mission segments will be accounted), and they will have the same format as the ones presently used by VASCOMP to model turboshaft engines.

Vehicle Sizing/Analysis

Step 11: VASCOMP is called upon to attempt a fuel balance iteration in order to size the entire vehicle. For the concept studied here, the rotor/engine sizing routine will use information provided directly by the rotor/engine sizing phase of this methodology rather than using the conventional approach used by VASCOMP to size typical turboshaft/turboprop aircraft. As the gross weight of the vehicle changes through the various iterations, the rotor aerodynamic / thermodynamic characteristics versus C_T/σ tables generated in Step 8 will be accessed rather than repeating the entire rotor/engine sizing procedure.

Step 12: Once convergence is achieved for this iterative scheme, all vehicle characteristics are set at this point and an optimization loop may be requested to assess the effect that altitude, airfoil thickness to chord ratio (t/c), wing loading (W/S), etc. have on the final solution. This way an optimum configuration for a given set of criteria (usually gross weight or life cycle cost) can be obtained.

Step 13: CRUISE4 and CRUISE5 can be utilized after the optimum design is finalized (off- or on-line) to calculate and present the vehicle's performance for both the helicopter and fixed-wing mode.

Concluding Remarks

The sizing methodology presented in this paper enables a designer to effectively analyze stopped, tip jet/CC rotor/wing configurations and to compare their performance to other high speed rotorcraft concepts. Because of this concept's unique usage of both reaction drive and Circulation Control, a strong coupling exists between its rotor and engine characteristics; therefore, these two subsystems cannot be sized independently. Since the rotor of a pressure jet driven configuration can be viewed as a component of the power plant cycle, its design will have to be based on aerodynamic, structural, and thermodynamic considerations. During the rotor design sizing and analysis process, the designer faces the task of determining those rotor parameters which will optimize the external blade aerodynamics (by minimizing blade profile drag) as well as minimize the internal thermodynamic losses in the blade ducts and at the same time keep the rotor structural weight as low as possible. The algorithm presented in this paper provides a much needed systematic approach for the synthesis of rotorcraft. This procedure is presently being implemented into a new code, TIPJET/CC, which links existing aerodynamic/thermodynamic and synthesis design tools (QNEP, CRUISE4, CRUISE5, VASCOMP) together in order to analyze as well as to optimize such concepts as the GTM-85.

Acknowledgments

The work presented in this paper was sponsored by NASA Ames' Systems Analysis Branch under a NASA Ames-University Consortium agreement for joint research entitled : Sizing and Performance Analysis of a Tip-Jet Driven High Speed Rotorcraft Concept. Mr. Thomas L. Galloway was the contract coordinator, as well as the technical monitor.

The authors would like to express at this point their gratitude and appreciation to Mr. Mark Waters (Eloret at NASA Ames) and Mr. Jim Phillips (Systems Analysis Branch NASA Ames) for the assistance and guidance given to them throughout the duration of this research task.

The contributions of Mr. Alan Schwartz (Carderock Division Naval Surface Warfare Center) to this study must also be acknowledged. Mr. Schwartz has been a key technical contributor to this investigation through his willingness to share various (experimental and analytical) documents describing different aspects of the CC rotor. By providing Georgia Tech with the latest versions of CRUISE4 and CRUISE5 and by making himself available for phone consultations, Mr. Schwartz has been a valuable asset to this investigation.

References

[1] Lovenguth, M., Martin, C., Mitchell, C., O'Rourke M., and Rutherford, J., "Technology Needs for High Speed Rotorcraft". NASA Contractor Report 177578 Prepared by McDonnell Douglas Helicopter Company, Mesa, Arizona for Ames Research Center, April 1991.

[2] Bartie, K.M., Schneider, J.J., and Wilkerson, J.B., "Technology Needs for High Speed Rotorcraft (1)". NASA Contractor Report 177585 Prepared by Boeing Helicopters, Philadelphia, Pennsylvania for Ames Research Center, May 1991.

[3] Scott, M.W., "Technology Needs for High Speed Rotorcraft (2)". NASA Contractor Report 177590 Prepared by Sikorsky Aircraft, Stratford, Connecticut for Ames Research Center, August 1991.

[4]Conway, S., and DeTore, J., "Technology Needs for High Speed Rotorcraft (3)". NASA Contractor Report 177592 Prepared by Bell Helicopter Textron, Inc., Fort Worth, Texas for Ames Research Center, October 1991.

[5]Stroub, R.H., "Introduction of the M-85 High Speed Rotorcraft Concept". NASA Technical Memorandum 102871, NASA Ames Research Center, Moffett Field, CA, January 1991.

[6]Smith, C.R., "Hot Cycle Rotor/Wing Composite Research Aircraft". Hughes Tool Company, Aircraft Division, Culver City, California, August 1968.

[7]Schwartz, A.W., "An Unmanned Air Vehicle Concept with Tip Jet Drive". Presented at the Specialists' Meeting on Vertical Lift Aircraft Design, San Francisco, CA, January 1990.

[8]Head, R.E., "Warm Cycle Propulsion for the 1990's Heavy Lift Helicopters". Presented at the Rotary Wing Propulsion System Specialist Meeting of the American Helicopter Society in Williamsburg, Virginia, November 16-18, 1982.

[9]Englar, R.J., "Investigation into and Application of the High Velocity Circulation Control Wall Jet for High Lift and Drag Generation on STOL Aircraft". Paper presented at the AIAA 7th Fluid and Plasma Dynamics Conference, Palo Alto, Ca, June 17-19, 1974.

[10]Mavris, D.N., Schrage, D.P., and Galloway T. L., "Mathematical Formulation and Design Methodology for a Tip Jet Driven High Speed Rotorcraft Concept". School of Aerospace Engineering, Georgia Institute of Technology, August 1991.

[11]Plencner, R.M. and Snyder, C.A., "The Navy/NASA Engine Program (NNEP89) -- A User's Manual". NASA Technical Memorandum 105186, August 1991.

[12]Geiselhart, K.A., Caddy, M.J., and Morris, S.J., Jr., "Computer Program for Estimating Performance of Air-Breathing Aircraft Engines". NASA Technical Memorandum 4254. Ames Research Center, May 1991.

[13]Curlett, B.P. and Ryall, K., "A Graphical User-Interface for Propulsion System Analysis". NASA Technical Memorandum 105696. Lewis Research Center, Cleveland, Ohio, August 1992.

[14]Hill, P.G. and Peterson, C.R. Mechanics and Thermodynamics of Propulsion. Addison-Wesley Publishing Company, Reading, Mass., 1965.

[15]Schoen, A.H., Rosenstein, H., Stanzione, K.A., and Wisniewski, J.S. "User's Manual for VASCOMP II The V/STOL Aircraft Sizing and Performance Computer Program". Prepared by Boeing Vertol Company, Philadelphia, Pennsylvania for NASA Ames Reasearch Center, May 1980 (Third Revision).